Grazing and heat stress protection of native grass by a sand-fixing shrub in the arid lands of northern China

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Abstract: Shrub species are used in restoration projects on dryland for their facilitation effects, which include environmental improvements and protection from herbivore feeding. Facilitation effects on forage grasses are potentially important in improving grazing capacity on rangelands. However, the morphology-dependent performance of benefactor plants in facilitating forage species growth and supplementation under moderate grazing intensity remains unclear. Here, our main purpose was to measure facilitation performance in terms of the survival of a native forage grass, *Agropyron cristatum* (L.) Gaertn. (Gramineae)., in accordance with the growth conditions of a sand-fixing benefactor shrub, *Caragana microphylla* Lam., in the Hulun Buir Grassland, northern China. Six study sites with patches of *A. cristatum* and *C. microphylla* were established at the foot of fixed sand dunes. At each site, five quadrats were set in places where *C. microphylla* coverage was 100% and *A. cristatum* grew among the shrubs (shrub quadrats), and another five were set where *A. cristatum* grew alone without *C. microphylla* (grass quadrats). We measured the morphological traits of *C. microphylla* and *A. cristatum* in all 60 quadrats, along with the soil water content and soil temperature. The data were compared between the shrub and grass quadrats by generalized linear mixed-effect models to assess the shrub's facilitation effects. We also used such models to elucidate the relationship between the average height of *C. microphylla* and the morphological traits of *A. cristatum* in the shrub quadrats. The maximum height, average grazed height, and the number of seed heads of *A. cristatum* were greater in the shrub quadrats than in the grass quadrats. The soil surface temperature was lower in the shrub quadrats. The maximum height and seed head number of *A. cristatum* were positively associated with the average height of *C. microphylla*. These results suggest that the grazing impact and heat stress were smaller in shrub quadrats than in grass quadrats, and that the degree of this protective effect depended on the shrub height. The shrub canopy seemed to reduce the increase in soil temperature and keep the grass vigorous. Livestock likely avoided grazing grasses in the *C. microphylla* patches because of the shrub's spiny leaves; only the upper parts of the grass stems (including the seed heads) protruding from the shrub canopy were grazed. The sand-fixing shrub thus moderates the grazing impact and soil temperature, and contributes to vegetation restoration and grazing system sustainability.

Keywords: *Caragana microphylla*; dryland; ecosystem restoration; facilitation; grazing impact; heat stress

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1 Introduction

Shrub species are often used as restoration tools on degraded arid lands because of their facilitation effects on other plants (Gómez-Aparicio et al., 2004; Padilla and Pugnaire, 2006; Zhao et al., 2007; Liczner et al., 2019). Facilitation is defined as a positive effect of one plant on another (Callaway, 1995; Stachowicz, 2001). Although competition has been considered the most important interaction related to plant community structure (Michalet and Pugnaire, 2016; Ploughe et al., 2019), facilitation is now considered a more important factor in highly stressful environments than in less stressful ones (Callaway and Walker, 1997; Maestre et al., 2009; Michalet and Pugnaire, 2016). Facilitation includes direct environmental improvements, such as canopy shading, and indirect positive effects such as physical protection from animal feeding (Stachowicz, 2001; Michalet and Pugnaire, 2016). Facilitation also helps to improve biodiversity (McIntire and Fajardo, 2014), resulting in diverse ecosystems with resilience in the face of climate change (Wright et al., 2017).

The cover and yield of palatable species, including native forage grass, are often used to evaluate grazing potential and grazing management plans (Seymour et al., 2010; Pittarello et al., 2019). Some research on plant facilitation effects has, therefore, focused on the dynamics of the contribution of forage species to grazing capacity improvement. Less palatable plants protect more palatable ones from herbivore grazing (Callaway et al., 2005; Baraza et al., 2006). Seed production ability, in addition, is linked to recovery from grazing damage and the dynamics of forage species (Crowley and Garnet, 2001). Facilitation effects on forage grass, especially on reproductivity, are potentially important in evaluating herbage production and sustainable land management decisions on rangelands.

Vegetation dynamics, taking between-plant facilitation and competition into account, are predicted mainly by the stress-gradient hypothesis (Bertness and Callaway, 1994) and by some of the hypotheses based on it (Butterfield, 2009; Maestre et al., 2009). In brief, the stress-gradient hypothesis predicts that the relative importance of positive and negative interactions will change inversely with gradients of physical stress (Bertness and Callaway, 1994). Butterfield (2009) developed conceptual models of vegetation community dynamics, taking facilitation into account, and identified the need for further research in areas of moderate environmental severity because of the complex dynamics caused by the interaction between competition and facilitation. Sand-fixing methods (e.g., use of straw checkerboards and shrub planting) can restore degraded lands by moderating environmental severities (e.g., reducing grazing and wind erosion, and improving soil nutrients) in the degraded lands (Li et al., 2009). Therefore, it is essential to understand the vegetation dynamics in the environments that are being restored by land rehabilitation techniques.

In addition, the relationship between benefactor size and facilitation performance is still unclear. The interactions between plants seem to change with plant size, because larger plants often have greater resource requirements and less sensitivity to climate change (Callaway and Walker, 1997; Le Roux et al., 2013). Martínez et al. (2004) found that the effect of shrubs on grass density under the canopy varied non-linearly with shrub size. López and Valdivia (2007), on the other hand, reported a positive correlation between cactus populations under shrubs and shrub canopy diameter. Despite the consistent results regarding the dependence of facilitation on benefactor size, little research has examined the relationship between benefactor size and facilitation performance (Tewksbury and Lloyd, 2001; Martínez et al., 2004; López and Valdivia, 2007). Information on this relationship would be useful for building sustainable rangeland systems.

We hypothesized that large shrub species would enhance the growth and supplementation of forage grass, in turn supporting the development of sustainable systems on grazed land. Our aims here were (1) to confirm the occurrence of shrub facilitation of a forage grass; and (2) to measure

the facilitation performance in accordance with the growth conditions of the shrub. To address these issues, we conducted a vegetation survey in a northern Chinese grassland.

2 Materials and methods

2.1 Study area and plants

This study was conducted in the Hulun Buir Grassland, Inner Mongolia, northern China (49°12′32″N, 118°89′90″E). The average annual precipitation is 300 to 350 mm mainly falling during the summer months. The annual average temperature ranges from −2.4°C to 2.2°C, and the frost-free period ranges from 100 to 120 d (Han et al., 2017). The main soil types in this area are Chernozems and Chestnut Soils (Liu et al., 2014). Excessive grazing has led to deterioration of the grassland (Guo et al., 2010), and there are many mobile sand dunes. For recovery of the grassland, the sand dunes have been fixed through the erection of fences around the dunes, placement of straw checkerboards, and sowing of the seeds of sand-fixing plants. Although the fencing seems to have moderated the grazing intensity in this area, there are traces of livestock entry (e.g. footprints, dung, and animal hairs) on the fixed dunes.

The dominant perennial vegetation of the area consists of the native shrub species *Caragana microphylla* Lam., which is also used for fixing dunes. It grows about 40 to 100 cm tall and flowers from May to June. Its stipules and leaf apices are spiny (Gu and Wang, 2009). Its seeds are often disseminated by local people to restore degraded land. Another major species here is *Agropyron cristatum* (L.) Gaertn. This forage grass is native to northern China, especially on the gravelly and sandy steppe. It grows about 15 to 80 cm tall and flowers from July to August (Gu and Wang, 2009). It is one of the perennial grasses that provide high-quality forage in the early growth stages (Hofmann et al., 1993).

2.2 Experimental design

Caragana microphylla was considered as the facilitating sand-fixing shrub and *A. cristatum* as the facilitated forage grass. These target plants grow on the foot of the sand dunes. Six sites (five with 30 m×30 m) were located between the dunes and the grassland (Fig. 1). Sites A and B were set at the foot of dunes that had been stabilized in 2014, and sites C and D at the foot of dunes that had been stabilized in 2013. These four dunes had been fenced and treated by straw checkerboard and sowing of seeds of sand-fixing plants. Site E was set at the foot of a mobile dune that had been simply surrounded by a fence in 2014 (with no straw checkerboard or seed sowing). Site F (15 m×60 m) was placed at the foot of a fixed dune, and it had been fenced off and treated by straw checkerboard in 2014 (but no seed sowing).

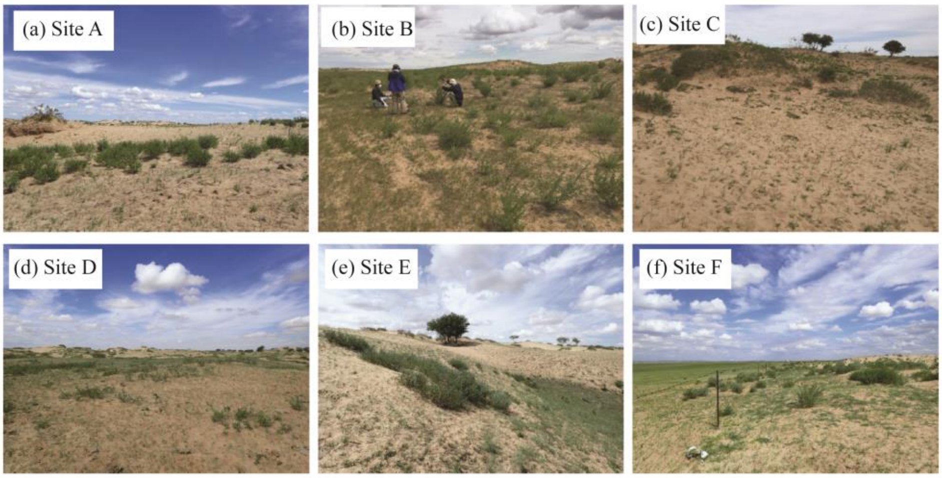

Fig. 1 Landscape of the experimental sites A–F

Ten quadrats (0.5 m×0.5 m) were set at each site. In the five shrub quadrats, the coverage of *C. microphylla* was 100% and *A. cristatum* grew within the *C. microphylla*. The five grass quadrats were set about 1.5 m distance from the shrub quadrates. In these quadrats, *A. cristatum* grew alone, with no *C. microphylla* (Fig. 2). In all 60 quadrats, we measured the height of *C. microphylla*, and the maximum height and average grazed height, total number of seed heads, and coverage of *A. cristatum*. We examined the edge of the grass stems to judge whether the grass had been grazed or not (Illius et al., 1995). If there was a shortened or no seed head at the end of the stem, we judged the stem to have been grazed and recorded the height as grazed height. In each quadrat, we measured the soil water content and soil temperature at three points (at about 5 cm depth) with an HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK) with a WET-2 sensor (Delta-T Devices Ltd., Cambridge, UK). We used the average values of the three points for statistical analysis. These measurements were conducted from 26 July to 5 August 2017.

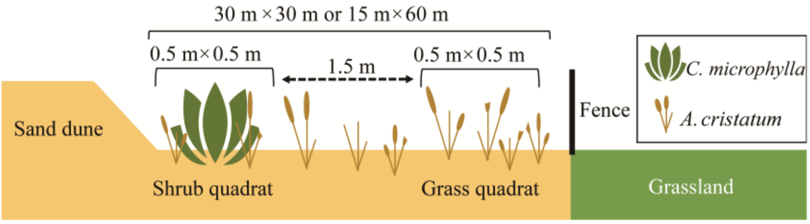

Fig. 2 Quadrat layout of this study

2.3 Data analysis

To elucidate whether the presence of *C. microphylla* improved the growth and survival of *A. cristatum*, and improved the soil water content and soil temperature, we applied generalized linear mixed-effect models (GLMMs) to the data from the quadrats. As response variables, we selected the maximum height, average grazed height, number of seed heads, and coverage of *A. cristatum*, soil water content, and soil temperature. We tested the data distributions and noted whether the variables were discrete or continuous in order to select the most suitable error distribution for the models (Table 1). Quadrat type (shrub or grass) was chosen as the explanatory variable. Survey site was considered as a random effect, mainly because of the differences in dune types and in environmental conditions caused by differences in location. We built models for the six response variables including the quadrat type and the random effect. By stepwise model selection, we chose the models with the minimum Akaike's information criterion (AIC) as the best (Burnham and Anderson, 2002). Each best model did not include the random effect. We tested the estimated slope in each best model to determine any difference between the quadrat types.

Table 1 Selected link functions and error distributions for GLMMs (generalized linear mixed-effect models)

Response variable	Link function	Error distribution
Maximum grass height	Identity link	Gaussian
Average grazed grass height	Log link	Gamma
Number of seed heads	Log link	Poisson
Grass coverage	Log link	Gamma
Soil water content	Log link	Gamma
Soil temperature	Identity link	Gaussian

To elucidate the performance of the shrub's protective effects on growth conditions, we created GLMMs with the shrub quadrat data, with the average height of *C. microphylla* as the explanatory variable. We selected the maximum height and the number of seed heads of *A. cristatum* as response variables because these indices seemed to be related to forage health and reproductivity (Pitelka et al., 1980; Baumhardt et al., 2011; Dawe et al., 2017). The same error distributions and link functions selected to elucidate the presence of shrub facilitation were used in these models.

The survey site was considered a random effect. We created GLMMs based on the error distribution of the response variables and chose the models with the minimum AIC as the best. The best model for the maximum grass height did not include the random effect. The best model for the number of seed heads of the grass, on the other hand, had an intercept that included the random effect of the sites. All data were analysed in R v. 4.1.1 software (R Core Team, 2022).

3 Results

3.1 Differences in grass trait and micro-environment in the two types of quadrat

Each best model did not include the random effect (i.e., the difference in the survey sites). There were differences between the shrub and grass quadrats in all selected response variables except grass coverage (Fig. 3; Table 2). The soil water content and soil temperature were higher in the grass quadrats. The maximum grass height, average grazed grass height, and seed head number were higher in the shrub quadrats.

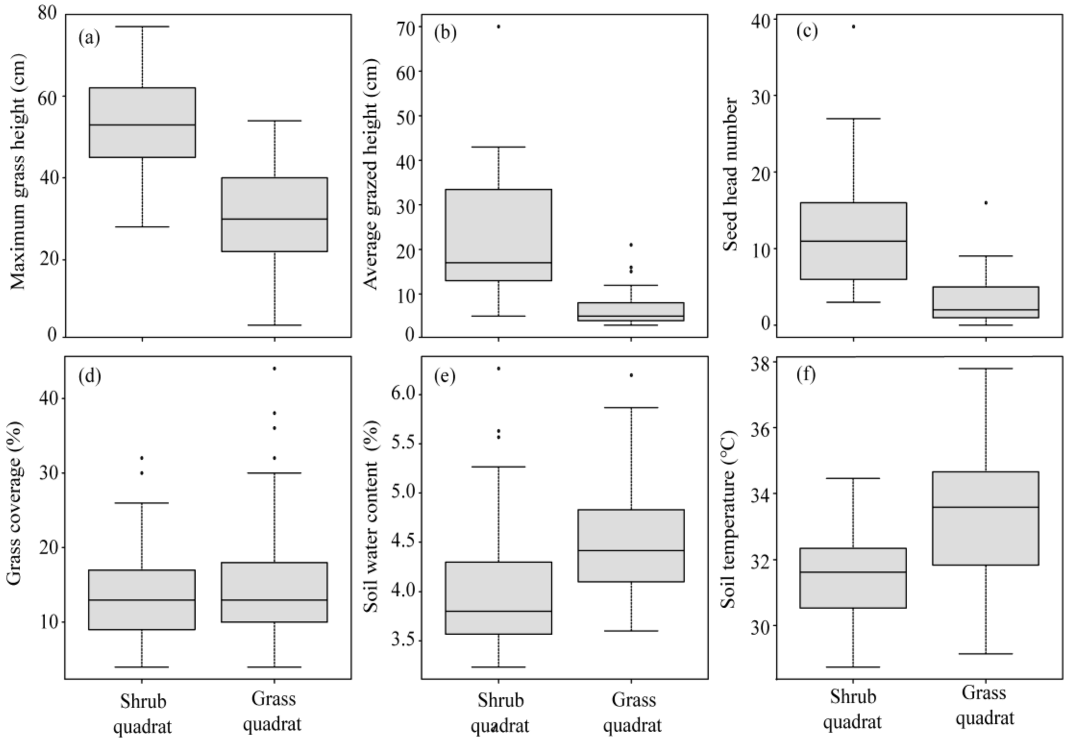

Fig. 3 Differences in grass traits and micro-environments between shrub and grass quadrats. (a), maximum grass height; (b), average grazed height; (c), seed head number; (d), grass coverage; (e), soil water content; (f), soil temperature. The box represents the 25th and 75th percentiles, and the whiskers are the upper and lower adjacent values. Circles are outliers.

Table 2 Model parameter estimates explaining the differences in grass traits and micro-environments between shrub and grass quadrats

Variable	Estimated slope	Standard error
Maximum grass height	**–22.29**	3.01
Average grazed grass height	**–1.20**	0.19
Number of seed heads	**–1.41**	0.12
Grass coverage	0.14	0.16
Soil water content	**0.11**	0.03

Soil temperature	**1.81**	0.49

Note: Each model was selected by AIC (Akaike's information criterion) value and did not include the random effect. This table shows the results of the six optimal models with the minimum AIC. Estimated slopes are in bold if $P<0.05$ level.

3.2 Extent of protective effect

The best model explaining the relationship between shrub height and the maximum grass height did not include the random effect. There was a positive association between the maximum height of *A. cristatum* and the average height of *C. microphylla* in the shrub quadrats (Fig. 4a; Table 3). On the other hand, the best model for the numbers of seed heads of the grass had an intercept that included the random effect of the survey sites. There was a positive association between the number of seed heads of the grass and the average height of *C. microphylla* in the shrub quadrats (Fig. 4b; Table 3).

Table 3 Model parameter estimates explaining the relationships between shrub height and grass traits

Variable	Estimated slope	Standard error
Maximum grass height	**0.360**	0.120
Intercept	**32.749**	6.869
Number of seed heads	**0.013**	0.004
Intercept	**1.700**	0.289

Note: This table shows the results of two optimal models with the minimum AIC. Quadrat type was treated as a categorical explanatory variable in the model for the number of seed heads, with shrub constituting a reference category. The estimates are in bold if $P<0.05$ level.

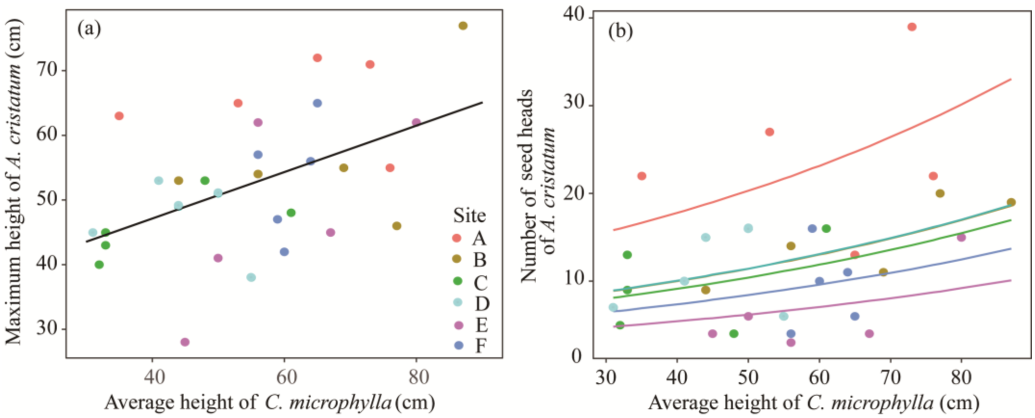

Fig. 4 Relationships of the average height of *Caragana microphylla* with (a) the maximum height and (b) the number of seed heads of *Agropyron cristatum* in the shrub quadrats. The best model of the relationship between the shrub height and the number of seed heads included the random effect of the survey sites.

4 Discussion

4.1 Protective effect and environmental moderation

One of our aims was to confirm the facilitation of the growth of grass plants by the presence of a shrub. We found differences in the traits of *A. cristatum*, except in coverage, between the shrub quadrats and the grass quadrats (Fig. 3; Table 2). The differences in the grass height and the number of seed heads seemed to be caused by the different grazing impacts in the two types of quadrats: the grazing impact was smaller in the shrub quadrats. Palatable plants in drylands may be protected from grazing if they grow near unpalatable plants (Callaway et al., 2005; Baraza et al., 2006; Koyama et al., 2015). *Caragana microphylla* has spiny leaves, and livestock tend to avoid grazing it (Katoh et al., 1988). These studies and our findings suggest that *C. microphylla* at our study sites protected *A. cristatum* from grazing.

There was, however, no difference in *A. cristatum* coverage between the shrub quadrats and the

grass quadrats (Fig. 3; Table 2). This might be explained by the grazing tolerance of the grass. Olson and Richards (1988) reported that *Agropyron desertorum* was tolerant of grazing, and its tillers could survive and regrow after moderate grazing. Therefore, it is possible that the spread of the tillers of *A. cristatum* at our sites did not depend on the existence of shrubs under moderate grazing pressure maintained by the fence.

Although *C. microphylla* at our study sites protected the forage grass from grazing, it can be defoliated under heavy grazing pressure (Katoh et al., 1988; Verwijmeren et al., 2019). Under the stress-gradient hypothesis, the facilitation effect is strengthened under high consumer pressure (Bertness and Callaway, 1994). However, it seems to work, and to be enhanced, only under certain levels of environmental severity (Katoh et al., 1988; Verwijmeren et al., 2019). Our result is consistent with these studies, because fencing of our sites seemed to moderate the grazing pressure. To better understand the level of grazing intensity in which the shrub protection remains effective, more detailed data sets are needed, including livestock movements and density.

Caragana microphylla moderated the surface soil temperature (Fig. 3; Table 2), as the canopy shade provided by shrubs moderates sunlight intensity (Padilla and Pugnaire, 2006). The canopy seemed to buffer the extremely hot temperatures on the soil surface. However, soil water content was lower in the shrub quadrats than in the grass quadrats (Fig. 3; Table 2). This might have been caused by competition for groundwater between *C. microphylla* and *A. cristatum* or by the interception of rainfall by the shrub canopy (Tielbörger and Kadmon, 2000).

Plant interactions can be both positive and negative, and can occur simultaneously (Callaway and Walker, 1997; Armas and Pugnaire, 2005; Verwijmeren et al., 2019). The balance of positive and negative interactions seems to change with environmental stresses, such as drought, precipitation, and intensity of grazing pressure (Bertness and Callaway, 1994; Baraza et al., 2006; Brooker et al., 2008; Ploughe et al., 2019). Competition and rainfall interception cause negative interactions related to plant water uptake (Tielbörger and Kadmon, 2000). One example of a positive interaction is hydraulic lift: water movement through roots from wetter deep soil layers to drier shallow layers (Richards and Caldwell, 1987). Our results for soil water content indicated that the negative influence of the shrub (consuming water) was stronger than the positive one (lifting water) under moderate grazing pressure. Our results, however, show the final balance of positive and negative effects, and do not delineate the extent of each. Feeding deuterated water to the roots of shrubs is one possible way to detect the amount of water that is supplied by the shrub to the grass (Armas et al., 2010), potentially leading to a better understanding of the plant–plant interaction balance.

4.2 Performance of protective effect in terms of *A. cristatum* reproductivity

The other aim of this study was to measure the extent of facilitation in accordance with the growth conditions of the shrub. The average height of *C. microphylla* had a positive association with the maximum height and the number of seed heads of *A. cristatum* (Fig. 4; Table 3). Grass height seems to be related to grass health (Pitelka et al., 1980; Dawe et al., 2017), and the number of seed heads is considered as an indicator of reproductive growth conditions (Baumhardt et al., 2011). Alday et al. (2016) reported that shrubs facilitate the establishment of oak seedlings, and that the effect depends on shrub height. Navarro-Cano et al. (2016) used shrub canopy diameter as a parameter of shrub age, and found that the rate of emergence of seedlings of some species increased with increasing shrub age (i.e., canopy diameter) in a seed sowing experiment. These studies focused on shrub facilitation of seedling establishment. To add to these findings, our results indicate that shrub facilitative effects on grass vigor and seed production depended on shrub height at our study sites.

Our results show that taller *C. microphylla* was more effective in improving *A. cristatum* vigor (Fig. 4; Table 3). This result might be explained by the shrub canopy, the presence of which can improve nearby micro-environmental conditions (Michalet and Pugnaire, 2016). High-temperature stress has a variety of effects on plants, including on growth (Hasanuzzaman et al., 2013; Jones et al., 2017). In our study, the surface-soil temperature was moderated in the

shrub quadrats (Fig. 3; Table 2), and this lower temperature may have helped to keep *A. cristatum* vigorous. Heat stress can also reduce seed quality and quantity (Prasad et al., 2017; Rashid et al., 2018). The cooler conditions caused by the shrub canopy might have led to greater production of seed heads.

Sustainable grazing cannot be realized if the livestock graze almost all of the grass, even if it has many seed heads. Grazing livestock responds to the physical and structural properties of fodder plants (Illius et al., 1995; Díaz et al., 2001) and to the characteristics of neighboring plants (Baraza et al., 2006). It is likely that, in our shrub quadrats, only the upper parts of the grass stems (including the spikes) that protruded from the shrubs were grazed, because of the protective effects of *C. microphylla* (Katoh et al., 1988). Our study and previous research indicate that *C. microphylla* should support forage grass establishment and growth (Alday et al., 2016; Navarro-Cano et al., 2016), as well as seed survival. Without excessive grazing pressure, these shrubs should ensure the annual sustainability of the forage grass, enabling the development of a sustainable grazing system.

5 Conclusions

We found differences in the traits of a native forage grass and environmental conditions between sites with and without sand-fixing shrubs under moderate grazing pressure. Shrub height was correlated with forage grass traits that related to health and reproductivity. Our results show that the presence of the sand-fixing shrub protected the native forage grass from high-temperature stress and livestock grazing to a degree dependent on shrub height under moderate grazing intensity. This protective effect might be attributed to the canopy and spikes of the shrubs, which improved the grass vigor and sustainability. Our findings should help to improve the understanding of plant dynamics with facilitation effects under moderate environmental stress, as well as their contribution to the long-term improvement of grazing-quality in arid lands.

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